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6. AUTHORS Ming C. Lin; Dinesh Manocha			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
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14. ABSTRACT 3D digital models of complex systems is often used to reduce design time, lower testing and validation cost, perform "virtual rehearsal", and rapid visualization of intricate datasets of varying scale: from nanometer-sized objects (e.g. nanoscale robots, storage devices and					
15. SUBJECT TERMS Virtual Prototyping, Multiresolution Algorithms, Real-time Visualization, Interaction					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Ming Lin
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 919-962-1974

## Report Title

Final Report for "Multiresolution Algorithms for Processing Giga-Models:  
Real-time Visualization, Reasoning, and Interaction"

### ABSTRACT

3D digital models of complex systems is often used to reduce design time, lower testing and validation cost, perform ``virtual rehearsal'', and rapid visualization of intricate datasets of varying scale: from nanometer-sized objects (e.g. nanoscale robots, storage devices and nanowheels), biological entities (e.g. human bodies), physical systems (e.g. chemical propagation), environmental data (e.g. terrain and urban environments), to large-scale man-made computer-aided design (CAD) structures (e.g. unmanned aerial vehicles, tanks and combat vehicles, underwater robots, and powerplants composed of many millions of parts).

In this proposal, we refer to the 3D digital representations of these extremely large and massive systems as ``giga-models''. To help fully realize the potential of virtual environments, the proposed research targets the solution of several important and well-defined problems, including interactive display, proximity queries, and physical simulation.

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**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

<u>Received</u>	<u>Paper</u>
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**TOTAL:**

**Number of Papers published in peer-reviewed journals:**

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**(b) Papers published in non-peer-reviewed journals (N/A for none)**

<u>Received</u>	<u>Paper</u>
2012/04/19 11: 57	Huai-Ping Lee, Ming Lin, Mark Foskey. Physically-Based Validation of Deformable Medical Image Registration, Medical Image Computing and Computer-Assisted Intervention, (09 2008): 830. doi:
2012/04/17 1: 35	Jeremy Wendt, William Baxter, Ipek Oguz, Ming Lin. Finite-Volume Flow Simulations in Arbitrary Domains, Graphical Models, (01 2007): 19. doi:
2012/04/17 1: 34	Naga Govindaraju, Ilknur Kabul, Ming Lin, Dinesh Manocha. Fast Continuous Collision Detection among Deformable Models using Graphics Processors, Computers and Graphics, (01 2007): 5. doi:
2012/04/17 1: 33	Young Kim, Stephane Redon, Ming Lin, Dinesh Manocha, Jim Templeman. Interactive Continuous Collision Detection using Swept Volume for Avatars, Presence, (04 2007): 206. doi:
2012/04/17 1: 32	Kelly Ward, Florence Bertails, Tae-Yong Kim, Stephen Marschner, Marie-Paule Cani, Ming Lin. A Survey on HairModeling: Styling, Simulation, and Rendering, IEEE Transactions on Visualization and Computer Graphics, (03 2007): 213. doi:
2012/04/17 1: 31	Kelly Ward, Nico Galoppo, Ming Lin. Interactive Virtual Hair Salon, Presence, (05 2007): 237. doi:
2012/04/17 1: 30	Theodore Kim, Jason Sewall, Avneesh Sud, Ming Lin. Fast Animation of Laplachian Growth, IEEE Computer Graphics and Applications, (03 2007): 68. doi:
2012/04/17 1: 29	Theodore Kim, Ming Lin. Fast Animation of Lightning Using Adaptive Meshes, IEEE Transactions on Visualization and Computer Graphics, (03 2007): 390. doi:
2012/04/17 1: 28	Theodore Kim, Ming Lin. Advection-Reaction-DiffusionWith Arbitrary Anisotropy, Journal of Computer animation and Virtual World, (09 2007): 329. doi:
2012/04/17 1: 27	Vivek Kwatra, David Adalsteinsson, Theodore Kim, Nipun Kwatra, Mark Carlson, Ming Lin. Texturing Fluids, IEEE Transactions on Visualization and Computer Graphics, (07 2007): 939. doi:
2012/04/17 1: 26	Nico Galoppo, Miguel Otaduy, Serhat Tekin, Markus Gross, Ming Lin. Fast Contact Dynamics for Deformable Articulated Characters, Computer Graphics Forum, (09 2007): 243. doi:
2012/04/17 1: 25	Vivek Kwatra, Philippos Mordohai, Rahul Narain, Sashi Kumar Penta, Mark Carlson, Marc Pollefeys, Ming Lin. Fluid in Video: Augmenting Real Video with Simulated Fluids, EuroGraphics, (04 2008): 487. doi:
2012/04/17 1: 24	Avneesh Sud, Erik Andersen, Sean Curtis, Ming Lin, Dinesh Manocha. Real-time Path Planning in Dynamic Virtual Environments Using Multi-agent Navigation Graphics, IEEE Transactions on Visualization and Computer Graphics, (05 2008): 526. doi:
2012/04/17 1: 23	Ming Lin, Avneesh Sud, Jur van den Berg, Russell Gayle, Sean Curtis, Hengchin Yeh, Stephen Guy, Erik Andersen, Sachin Patil, Jason Sewall, Dinesh Manocha. Real-time path Planning and Navigation for Multi-agent and Crowd Simulations, Lecture Notes in Computer Science, (01 2008): 23. doi:
2012/04/17 1: 22	Ming Lin, Stephen Guy, Rahul Narain, Jason Sewall, Sachin Patil, Jatin Chhugani, Abhinav Golas, Jur van den Berg, Sean Curtis, David Wilkie, Paul Merrell, Changkyu Kim, Nadathur Satish, Pradeep Dubey, Dinesh Manocha. Interactive Modeling, Simulation and Control of Large-Scale Crowds and Traffic, Lecture Notes in Computer Science, (11 2009): 94. doi:
2012/04/17 1: 21	William Moss, Ming Lin, Dinesh Manocha. Constraint-based Motion Synthesis for Deformable Models, Computer animation and Virtual Worlds, (09 2008): 421. doi:
2012/04/17 1: 20	Rahul Narain, Jason Sewall, Mark Carlson, Ming Lin. Fast Animation of Turbulent Flows Using EnergyTransport and Procedural Synthesis, ACM Transactions on Graphics, (12 2008): 166. doi:

2012/04/17 1: 19 Russell Gayle, Avneesh Sud, Erik Andersen, Stephen Guy, Ming Lin, Dinesh Manocha. Interactive Navigation of Heterogeneous Agents Using Adaptive Roadmaps, IEEE Transactions on Visualization and Computer Graphics, (01 2009): 34. doi:

2012/04/17 1: 18 Jason Sewall, Nico Galoppo, Georgi Tsankov, Ming Lin. Visual Simulation of Shockwaves, Graphical Models, (07 2009): 126. doi:

2012/04/17 1: 17 Rahul Narain, Abhinav Golas, Sean Curtis, Ming Lin. Dynamics for Dense Crowd Simulation, ACM Transactions on Graphics, (12 2009): 122. doi:

2012/04/17 1: 16 Jason Sewall, Jur Van Den Berg, Ming Lin, Dinesh Manocha. Virtualized Traffic: Reconstructing Traffic Flows from Discrete Spatio-Temporal Data, IEEE Transactions on Visualization and Computer Graphics, (01 2011): 26. doi:

2012/04/16 1: 14 Jia Pan, Liangjun Zhang, Ming Lin, Dinesh Manocha. A Hybrid Approach for Simulating Human Motion in Constrained Environments, Computer animation and Virtual Worlds, (05 2010): 137. doi:

2012/04/16 1: 12 Ming Lin, Dinesh Manocha. Virtual Cityscapes: Recent Advances in Crowd Modeling and Traffic Simulation", Frontiers of Computer Science in China, (09 2010): 405. doi:

2012/04/16 1: 10 Sachin Pail, Jur van der Berg, Sean Curtis, Ming Lin, Dinesh Manocha. Directing Crowd Simulations Using Navigation Fields, IEEE Transactions on Visualization and Computer Graphics, (02 2011): 244. doi:

2012/04/16 1: 9 Yu Zheng, Ming Lin, Dinesh Manocha. Efficient Simplex Computation for Fixture Layout Design, Computer Aided Design, (10 2011): 1307. doi:

2012/04/16 1: 8 Ravish Mehra, Nikunj Raghuvanshi, Lauri Savioja, Ming Lin, Dinesh Manocha. An Efficient GPU-based TimeDomain Solver for Acoustic Wave Equation, Applied Acoustics, (02 2012): 83. doi:

**TOTAL: 26**

**Number of Papers published in non peer-reviewed journals:**

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**(c) Presentations**

Keynote Speaker, Computer Animation and Social Agents, Chengdu, China, May 2011.

Invited Speaker, CRA-W Graduate Cohort Workshop, Boston, April 2011.

Invited Speaker, CRA-W Graduate Cohort Workshop, Bellevue, April 2010.

Invited Speaker, Workshop on City Modeling, Simulation, and Visualization, Shenzhen, China, April 2010.

Invited Speaker, Workshop on IT in Virtual Environments, Shenzhen, China, April 2010.

Invited Speaker, Motion in Games, Utrecht, Netherlands, Nov. 2009.

Keynote Speaker, IADIS International Conference on Computer Graphics and Visualization, Portugal, June 2009.

Keynote Speaker, ACM Symposium on Virtual Reality Software and Technology, Bordeaux, France, October 2008.

Invited Speaker, Motion in Games, Utrecht, Netherlands, June 2008.

Invited Speaker, SIAM Conference on Discrete Mathematics Mini-Symposium on Computational Geometry and Topology and Their Applications, June 2008.

Invited Speaker, IPAM Workshop on Scientific Computing Applications in Surgical Simulation of Soft Tissues, Los Angeles, January 2008.

Keynote Speaker, XVII Spanish Computer Graphics Conference (CEIG), Zaragoza, September 2007.

Keynote Speaker, EDUTAINMENT, Hong Kong, June 2007.

Invited Speaker, Workshop on Swarming in Natural and Engineered Systems, Philadelphia, May 2007.

Invited Speaker, DARPA Workshop on the Future of Constructive Simulations, January 2007.

**Number of Presentations:**      15.00

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**Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

<u>Received</u>	<u>Paper</u>
2012/04/19 1 68	Avneesh Sud, Erik Andersen, Sean Curtis, Ming Lin, Dinesh Manocha. Real-time Path Planning for Virtual Agents in Dynamic Environments, IEEE Virtual Reality . 2007/03/10 00:00:00, . : ,
2012/04/19 1 67	Russell Gayle, Ming Lin, Dinesh Manocha. Efficient Motion Planning of Highly Articulated Chains using Physics-based Sampling, IEEE International Conference on Robotics and Automation. 2007/04/10 00:00:00, . : ,
2012/04/19 1 66	Ilknur Kabul, Russell Gayle, Ming Lin. Cable Route Planning in Complex Environments Using Constrained Sampling, ACM Symposium on Solid and Physical Modeling and Applications. 2007/06/17 00:00:00, . : ,
2012/04/19 1 65	Nico Galoppo, Serhat Tekin, Miguel Otaduy, Markus Gross, Ming Lin. Interactive Haptic Rendering of High-Resolution Deformable Objects, Human Computer Interface International Symposium on Virtual Reality . 2007/07/14 00:00:00, . : ,
2012/04/19 1 64	Rahul Narain, Vivek Kwatra, Huai-Ping Lee, Theodore Kim, Mark Carlson, Ming Lin. Feature-Guided Dynamic Texture Synthesis on Continous Flows, Eurographics Symposium on Rendering. 2007/06/25 00:00:00, . : ,
2012/04/19 1 63	Jason Sewall, Paul Mecklenburg, Sorin Mitran, Ming Lin. Fast Fluid Simulation Using Residual Distribution Schemes, Eurographics Workshop on Nautral Phenomena. 2007/09/04 00:00:00, . : ,
2012/04/19 1 62	Russell Gayle, Avneesh Sud, Ming Lin, Dinesh Manocha. Reactive Deformation Roadmaps: Motion Planning of Mutilple Robots in Dynamic Environments, IEEE/RSJ International Conference on Intelligent Robots. 2007/10/29 00:00:00, . : ,
2012/04/19 1 61	Avneesh Sud, Russell Gayle, Erik Andersen, Stephen Guy, Ming Lin, Dinesh Manocha. Real-Time Navigation of Independent Agents Using Adaptive Roadmaps, ACM Symposium on Virtual Reality Software and Technology. 2007/11/05 00:00:00, . : ,
2012/04/19 1 60	Jur van den Berg, Sachin Patil, Jason Sewall, Dinesh Manocha, Ming Lin. Interactive Navigation of Multiple Agents in Crowded Environments, ACM Symposium on Interactive 3D Graphics and Games. 2008/02/15 00:00:00, . : ,
2012/04/19 1 59	Jur van den Berg, Ming Lin, Dinesh Manocha. Reciprocal Velocity Obstacles for Real-Time Multi-Agent Navigation, IEEE International Conference on Robotics and Automation. 2008/05/19 00:00:00, . : ,
2012/04/19 1 58	Nikunj Raghuvanshi, Nico Galoppo, Ming Lin. Accelerated Wave-based Acoustic Simulation, ACM Symposium on Solid and Physical Modeling. 2008/06/02 00:00:00, . : ,
2012/04/19 1 56	Jason Sewall, Nico Galoppo, Georgi Tsankov, Ming Lin. Visual Simulation of Shockwaves, Eurographics/ACM SIGGRAPH Symposium on Computer Animation. 2008/07/07 00:00:00, . : ,
2012/04/19 1 55	Hengchin Yeh, Sean Curtis, Sachin Patil, Jur van den Berg, Dinesh Manocha, Ming Lin. Composite Agents, Eurographics/ACM SIGGRAPH Symposium on Computer Animation. 2008/07/07 00:00:00, . : ,
2012/04/19 1 54	Jur van den Berg, Mike Stilman, James Kuffner, Ming Lin, Dinesh Manocha. Path Planning among Movable Obstacles: a Probabilistically Complete Approach, International Workshop on Algorithhmics of Robotics. 2008/12/07 00:00:00, . : ,
2012/04/19 0 53	Nico Galoppo, Miguel Otaduy, William Moss, Jason Sewall, Sean Curtis, Ming Lin. Controlling Deformable Models with Dynamic Morph Targets, ACM Symposium on Interactive 3D Graphics. 2009/02/27 00:00:00, . : ,
2012/04/19 0 52	Jur van den Berg, Jason Sewall, Ming Lin, Dinesh Manocha. Virtualized Traffic: ReconstructingTraffic Flows from Discrete Spatio-Temporal Data, IEEE Virutal Reality . 2009/03/14 00:00:00, . : ,
2012/04/19 0 51	Russell Gayle, William Moss, Ming Lin, Dinesh Manocha. Multi-Robot Coordination using Generalized Social Potential Fields, IEEE International Conference on Robotics and Automation. 2009/05/12 00:00:00, . : ,

- 2012/04/19 0: 50 Nikunj Raghuvanshi, Brandon Lloyd, Naga Govindaraju, Ming Lin. Efficient Numerical Acoustic Simulation on Graphics Processors Using Adaptive Rectangular Decomposition, EAA Symposium on Auralization. 2009/06/15 00:00:00, . : ,
- 2012/04/19 0: 49 Jur van den Berg, Jack Snoeyink, Ming Lin, Dinesh Manocha. Centralized Path Planning for Multiple Robots: Optimal Decoupling into Sequential Plans, Robotics: Science and Systems. 2009/06/28 00:00:00, . : ,
- 2012/04/19 0: 48 Jur van den Berg, Stephen Guy, Ming Lin, Dinesh Manocha. Reciprocal n-body Collision Avoidance, International Symposium on Robotics Research. 2009/08/31 00:00:00, . : ,
- 2012/04/19 0: 47 Stephen Guy, Jatin Chhugani, Changkyu Kim, Nadathur Satish, Ming Lin, Dinesh Manocha, Pradeep Dubey. ClearPath: Highly Parallel Collision Avoidance for Multi-Agent Simulation, ACM SIGGRAPH/EUROGRAPHICS Symposium on Computer Animation. 2009/08/01 00:00:00, . : ,
- 2012/04/19 0: 45 Yu Zheng, Ming Lin, Dinesh Manocha. A Fast n-Dimensional Ray-Shooting Algorithm for Grasping Force Optimization, IEEE International Conference on Robotics and Automation. 2010/05/03 00:00:00, . : ,
- 2012/04/19 0: 44 Huai-Ping Lee, Mark Foskey, Marc Niethammer, Ming Lin. Physically-Based Deformable Image Registration with Material Property and Boundary Condition Estimation, International Symposium on Biomedical Imaging. 2010/06/21 00:00:00, . : ,
- 2012/04/19 0: 43 Stephen Guy, Ming Lin, Dinesh Manocha. Modeling collision avoidance behavior for virtual humans, International Conference on Autonomous Agents and Multiagent Systems. 2010/05/10 00:00:00, . : ,
- 2012/04/19 0: 42 Yu Zheng, Ming Lin, Dinesh Manocha, Albertus Hedrawan Adiwahono, Chee-Meng Chew. A walking pattern generator for biped robots on uneven terrains, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). 2009/10/11 00:00:00, . : ,
- 2012/04/19 0: 41 Yu Zheng, Ming Lin, Dinesh Manocha. Efficient Simplex Computation for Fixture Layout Design, ACM Symposium on Solid and Physical Modeling. 2010/09/01 00:00:00, . : ,
- 2012/04/19 0: 39 Jens Schneider, Dina Garatly, Madhusudhanan Srinivasan, Stephen Guy, Sean Curtis, Steven Cutchin, Dinesh Manocha, Ming Lin , Alyn Rockwood. Towards a Digital Makkah- Using Immersive 3D Environments to Train and Prepare Pilgrims, International Conference on Digital Media and its Applications in Cultural Heritage (DMACH). 2011/03/12 00:00:00, . : ,
- 2012/04/17 1: 38 David Wilkie, Jur van den Berg, Ming Lin , Dinesh Manocha. Self-Aware Traffic Route Planning, AAAI Conference on Artificial Intelligence. 2011/08/07 00:00:00, . : ,
- 2012/04/17 1: 37 Zhixiang Wang, Dangxiao Wang, Yuru Zhang, Ming Lin. Analysis on increasing transparency for penalty-based six degree-of-freedom haptic rendering, World Haptics Conference. 2011/06/21 00:00:00, . : ,
- 2012/04/17 1: 36 Stephen Guy, Sujeong Kim, Ming Lin, Dinesh Manocha. Simulating Heterogeneous Crowd Behaviors Using Personality Trait Theory, ACM SIGGRAPH Symposium on Computer Animation. 2011/08/05 00:00:00, . : ,
- 2012/04/17 1: 15 Jason Sewall, David Wilkie, Paul Merrell, Ming Lin. Continuum Traffic Simulation, Eurographics 2012. 2010/05/04 00:00:00, . : ,
- 2012/04/16 1: 11 Rahul Narain, Abhinav Golas, Ming Lin. Free-Flowing Granular Materials with Two-Way Solid Coupling, SIGGRAPH Asia. 2010/12/15 00:00:00, . : ,
- 2012/04/16 1: 7 Jason Sewall, David Wilkie, Ming Lin. Interactive Hybrid Simulation of Large-Scale Traffic, ACM Transactions on Graphics (Proc. of SIGGRAPH Asia). 2011/12/15 00:00:00, . : ,
- 2012/04/16 1: 6 Sean Curtis, Ming Lin, Dinesh Manocha. Walk This Way: A Lightweight, Data-driven Walking Synthesis Algorithm, The Fourth International Conference on Motion in Games. 2011/11/15 00:00:00, . : ,

**TOTAL: 34**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

---

**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

Received

Paper

**TOTAL:**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

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**(d) Manuscripts**

Received

Paper

**TOTAL:**

Number of Manuscripts:

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**Books**

Received

Paper

**TOTAL:**

**Patents Submitted**

None submitted. Many software systems publicly available for download to be used for NON-COMMERCIAL

PURPOSES at: <http://gamma.cs.unc.edu/>

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**Patents Awarded**

None submitted.

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**Awards**

Ming C. Lin: IEEE VGTC Technical Achievement Award, Fellow of ACM 2011, Fellow of IEEE 2012, and 4 Best Paper Award (2007-2011)

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Dinesh Manocha: Fellow of ACM 2010, Fellow of AAAS 2011, Distinguished Alumni Award, IIT Delhi, Fellow of IEEE 2011, and 5 Best Paper Award (2006-2011)

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**Graduate Students**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	<u>Discipline</u>
Russell Gayle	0.50	
Nico Galloppo	0.50	
Stephen Guy	0.50	
Rahul Narain	0.50	
Jason Sewall	0.50	
<b>FTE Equivalent:</b>	<b>2.50</b>	
<b>Total Number:</b>	<b>5</b>	

**Names of Post Doctorates**



<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Avneesh Sud	0.25
Jur van den Berg	0.25
<b>FTE Equivalent:</b>	<b>0.50</b>
<b>Total Number:</b>	<b>2</b>

### Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Ming C. Lin	0.10	
Dinesh Manocha	0.10	
<b>FTE Equivalent:</b>	<b>0.20</b>	
<b>Total Number:</b>	<b>2</b>	

### Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Erik Andersen	0.25	Computer and Computational Sciences
<b>FTE Equivalent:</b>	<b>0.25</b>	
<b>Total Number:</b>	<b>1</b>	

### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 1.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 1.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ..... 1.00

### Names of Personnel receiving masters degrees

NAME

**Total Number:**

### Names of personnel receiving PHDs

NAME

Nico Gallopo

Russell Gayle

Rahul Narain

Jason Sewall

**Total Number:** 4

**Names of other research staff**

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

**Sub Contractors (DD882)**

**Inventions (DD882)**

**Scientific Progress**

The underlying theme of this project is design of novel algorithms and systems based on the "multiresolution" framework, i.e. describing geometry, spatial arrangements, numerics, and physical simulation across different scales. With the increasing complexity of large systems, this approach can potentially offer a robust and efficient solution that scales up to large size problems and adequately models the mutual interaction among multiple entities in complex mechanical, physical or biological systems. On one hand, such techniques allow the designers, scientists, and engineers to rapidly validate the existing design or explore new hypotheses. On the other hand, it can also enable the commanders and the soldiers on the battle field to quickly visualize information and interact with various entities on the "virtual battleground".

We addressed key issues in the realization of visualization, modeling and simulation techniques for handling giga-models.

These include new

level-of detail representations and novel multiresolution algorithms for interactive display, proximity query, and physics-based simulation and manipulation of massive datasets or giga-models. Specifically, we designed and developed the following new algorithms, software libraries and systems:

- (1) scalable proximity query algorithms using dual hierarchies;
- (2) continuous collision detection employing multiresolution swept volume;
- (3) fast dynamics computations with multi-level acceleration;
- (4) real-time display based on dynamically computed level-of-detail representations;
- (5) interactive walkthrough of giga-models.

The new algorithms and public-domain libraries offer fundamental advances for other research areas, including robotics and automation, computer graphics, rapid prototyping of nano-structures, etc.

### **Technology Transfer**